



Introduction

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High-resolution wave dynamics in the lower solar atmosphere

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The magnetic and convective nature of the Sun's photosphere provides a unique platform from which generated waves can be modelled, observed and interpreted across a wide breadth of spatial and temporal scales. As oscillations are generated *in-situ* or emerge through the photospheric layers, the interplay between the rapidly evolving densities, temperatures and magnetic field strengths provides dynamic evolution of the embedded wave modes as they propagate into the tenuous solar chromosphere. A focused science team was assembled to discuss the current challenges faced in wave studies in the lower solar atmosphere, including those related to spectropolarimetry and radiative transfer in the optically thick regions. Following the Theo Murphy international scientific meeting held at Chicheley Hall during February 2020, the scientific team worked collaboratively to produce 15 independent publications for the current Special Issue, which are introduced here. Implications from the current research efforts are discussed in terms of upcoming next-generation observing and high-performance computing facilities.

This article is part of the Theo Murphy meeting issue 'High-resolution wave dynamics in the lower solar atmosphere'.

1. Introduction

The topic of waves and oscillations in the Sun's atmosphere has been a focal point of solar physics research since their first detection over half a century ago [1,2]. The concentrated magnetic fields that permeate the entire solar surface are able to act as efficient waveguides for the oscillatory behaviour, hence providing conduits for the flow of wave energy upwards into the outer regions of the solar corona [3]. With the lower solar atmosphere, comprising the photosphere and chromosphere, being predominantly visible in the infrared, optical and ultraviolet portions of the electromagnetic spectrum, it becomes possible to observe these tenuous regions using a combination of ground-based and space-borne facilities.

In recent decades, modern upgrades to existing observatories (e.g. the Dunn, Swedish and Goode Solar Telescopes; [4–6]), in addition to the construction and/or launch of new observing facilities (e.g. Hinode, the Interface Region Imaging Spectrograph, the National Science Foundation's Daniel K. Inouye Solar Telescope; [7–9]), have paved the way for rapid advancements to be made in the field of lower atmospheric dynamics. In particular, the high spatial, temporal and spectral resolutions now available from the cutting-edge observatories, in combination with polarimetric capabilities, we have at our disposal have made the studies of small-scale oscillatory phenomena possible, resulting in numerous high-impact publications in recent years (e.g. [10–16]).

In response to the rapid progress made in the understanding of wave physics in the lower solar atmosphere, a dedicated team was formed in 2017 to continue to build upon developing worldwide expertise and to define new scientific challenges that could be tackled in the years and decades to come. The Waves in the Lower Solar Atmosphere¹ (WaLSA) team was formed, and initially consisted of 12 core members spanning seven countries. Following initial face-to-face meetings in Oslo, Norway, which were funded by the Research Council of Norway (through its Centres of Excellence scheme, the Rosseland Centre for Solar Physics), seed projects based on existing data were created to bolster collaborative partnerships between the team members and their affiliated research institutes. Success of these initial collaborations (e.g. [15,17–20]) prompted the WaLSA team coordinators to apply for additional funding to support a dedicated, multi-day meeting where both early career and well-established scientists could be invited to join the WaLSA team in order to define new, long-term goals under the scientific umbrella of wave activity in the lower solar atmosphere.

Funding was provided by The Royal Society Hooke Committee, through the award of a Theo Murphy Meeting that would take place at Chicheley Hall, England, UK, during 10–11 February 2020 (figure 1). Including the 12 core WaLSA team members, the Theo Murphy Meeting welcomed 28 participants from around the world for an intensive 2-day meeting. Following the successful presentations and discussions at the 'High-resolution wave dynamics in the lower solar atmosphere' meeting, sufficient scientific momentum was generated to enable a special themed issue of the *Philosophical Transactions of the Royal Society A* (<https://royalsocietypublishing.org/journal/rsta>) to be published based on the scientific achievements of the participating cohort and their extended collaborative networks.

When assembling both the original WaLSA team and the larger scientific group present at the Theo Murphy Meeting in February 2020, it was paramount to ensure that diversity, in terms of career stage, gender, race and geographical location, was achieved in order to most readily support the next generation of active solar physics researchers in the field. Of the 28 participants registered for the 'High-resolution wave dynamics in the lower solar atmosphere' meeting, over 25% were female and included career stages spanning the very first year of their

¹WaLSA team initiatives can be viewed at [www.WaLSA.team](http://WaLSA.team).



Figure 1. The Royal Society advertisement for the Theo Murphy Meeting 'High resolution wave dynamics in the lower solar atmosphere' (left), alongside a picture of the assembled team in front of Chicheley Hall during the meeting on 10–11 February 2020 (right). From left-to-right, the people visible in the photo are Dr David Jess, Dr Robert Sych, Mr Samuel Skirvin, Dr Peter Keys, Dr Elena Kholomenko, Prof. Tony Arber, Mr Conor MacBride, Dr Gary Verth, Dr Samuel Grant, Dr Rebecca Centeno Elliott, Dr Ben Snow, Dr Matthias Rempel, Dr Aimee Norton, Dr Alex Feller, Mr Callum Boocock, Mr Daniele Calchetti, Dr Marco Stangalini, Dr Bernhard Fleck, Prof. Stuart Jefferies, Dr Shahin Jafarzadeh and Ms. Anwar Aldhafeeri.

PhD, through to senior professorial academics at prestigious, globally recognized universities (see, e.g. those listed in [table 1](#)). Furthermore, when considering both the countries of origin and the current research institutes of the WaLSA team and Theo Murphy Meeting delegates, 23 countries are incorporated into the worldwide collaborative network provided by The Royal Society Hooke Committee funding ([figure 2](#)). The widespread nature of WaLSA activities ensures that, at present, approximately 45% of the Earth's landmass is linked to researchers undertaking cutting-edge studies of waves in the Sun's lower atmosphere through engagement with the WaLSA scheme. However, it can be seen from [figure 2](#) that scientific links with continental Africa are currently missing; something that has been documented across all fields of science in recent years [21]. Thankfully, new initiatives including the UK–South Africa Newton Fund² and The Royal Society's International Exchange³ programmes may help facilitate bilateral involvement with developing African research centres, something which the WaLSA team looks forward to actively engaging with over the coming years.

2. Publications in the Special Issue

The themed Special Issue of the *Philosophical Transactions of the Royal Society A*, based around the Theo Murphy Meeting 'High-resolution wave dynamics in the lower solar atmosphere', incorporates 15 novel publications (excluding this preface) that are at the forefront of current research efforts around the world. Submissions for the Special Issue began in May 2020, with the manuscripts peer reviewed by international experts in the field, alongside scientific and editorial guidance from the Guest Editors Drs. Jess, Keys, Stangalini and Jafarzadeh. Even with the rigorous peer review process in place, an average submission-to-acceptance time frame of 69 ± 23 days was achieved, which recognizes the dedication given to the Special Issue by both the authors and international peer reviewers alike.

²<https://www.newtonfund.ac.uk/about/about-partner-countries/south-africa/>.

³<https://royalsociety.org/grants-schemes-awards/grants/international-exchanges/>.

Table 1. Summary of contributions to the WaLSA research team and the themed Special Issue of the *Philosophical Transactions of the Royal Society A*, organized alphabetically by country to document the affiliated research institutes.

country	research institute
Australia	School of Mathematical and Physical Sciences, University of Newcastle
Belgium	Centre for mathematical Plasma Astrophysics (CmPA), KU Leuven
Chile	School of Engineering, Pontificia Universidad Católica de Chile
China	National Astronomical Observatories, Chinese Academy of Science
	School of Astronomy and Space Sciences, University of Chinese Academy of Sciences
Germany	Leibniz-Institut für Sonnenphysik (KIS)
	Max Planck Institute for Solar System Research, Göttingen
Italy	ASI Italian Space Agency
	Department of Physics, University of Rome Tor Vergata
	INAF-OAR National Institute for Astrophysics
Norway	Institute of Theoretical Astrophysics, University of Oslo
	Rosseland Centre for Solar Physics, University of Oslo
Russia	Institute of Solar-Terrestrial Physics SB RAS
Saudi Arabia	Mathematics Department, Majmaah University
Spain	Departamento de Astrofísica, Universidad de La Laguna
	Instituto de Astrofísica de Canarias
Switzerland	Istituto Ricerche Solari Locarno (IRSOL)
UK	Astrophysics Research Centre, Queen's University Belfast
	Centre for Geophysical and Astrophysical Fluid Dynamics, University of Exeter
	Department of Mathematics, Northumbria University
	Plasma Dynamics Group:
	School of Mathematics and Statistics, University of Sheffield
	Department of Automatic Control and Systems Engineering, University of Sheffield
	University College London, Mullard Space Science Laboratory
USA	Ben T. Zinn Combustion Laboratory, Georgia State University
	Center for Solar-Terrestrial Research, New Jersey Institute of Technology
	College of Science, George Mason University
	Department of Physics and Astronomy, California State University Northridge
	Department of Physics and Astronomy, Georgia State University
	ESA Science and Operations Department, c/o NASA/GSFC Code 671
	Hansen Experimental Physics Laboratory, Stanford University
	High Altitude Observatory, NCAR
	Institute for Astronomy, University of Hawaii
	National Solar Observatory (NSO)
	Natural and Applied Sciences, University of Wisconsin
	Space Vehicles Directorate, Air Force Research Laboratory

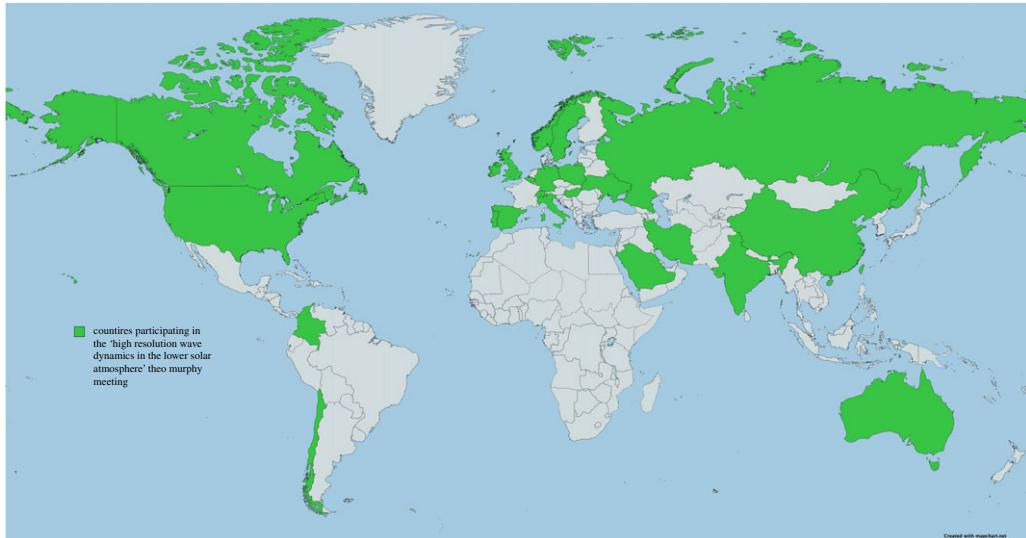


Figure 2. A world map, where both the countries of origin and the current institutes of researchers contributing to the workshops and publications featured in the Special Issue of the *Philosophical Transactions of the Royal Society A* are highlighted in green. The countries highlighted amount to approximately 45% of the Earth's total landmass (23 countries in total), showing the widespread influence of research feeding into The Royal Society's Special Issue. Image courtesy of www.mapchart.net.

In total, the Special Issue comprises 55 unique authors spanning 34 research institutes, highlighting the global collaborative work undertaken in response to the funding provided by The Royal Society's Hooke Committee. While all of the publications are central to the theme of wave activity in the lower solar atmosphere, some document theoretical and/or numerical findings, while others highlight developments in the observational analyses of high-resolution photospheric and/or chromospheric datasets. The subsections below summarize the contributions to the Special Issue by breaking them up into overarching specialist subject areas.

(a) Cover art for the Special Issue

Due to the large number of publications being written and accepted for the Special Issue of the *Philosophical Transactions of the Royal Society A*, it was possible to select a single striking, relevant image that encapsulated the *High-resolution wave dynamics in the lower solar atmosphere* theme of the published manuscripts. Each of the lead authors from the Special Issue were invited to submit (or recommend) an image for consideration that depicted an observational, simulated and/or artistic impression of wave activity in the lower solar atmosphere. In total, nine submitted images were received, which are shown in figure 3. Captions for each of the nine potential cover art submissions, alongside the corresponding image credits, are appended below.

- (a) Image of a highly magnetic active region as captured in the chromospheric H α line (656.3 nm) by the Hydrogen-Alpha Rapid Dynamics camera (HARDcam; [22]) instrument at the National Science Foundation's Dunn Solar Telescope in New Mexico, USA. The dark sunspot umbra towards the centre of the field-of-view reveals much cooler material as a result of the strong magnetic fields inhibiting the convective mixing of the surrounding plasma. Sunspots play a pivotal role in the guiding of wave motion due to their concentrated magnetic fields.

Image credit: David B. Jess.

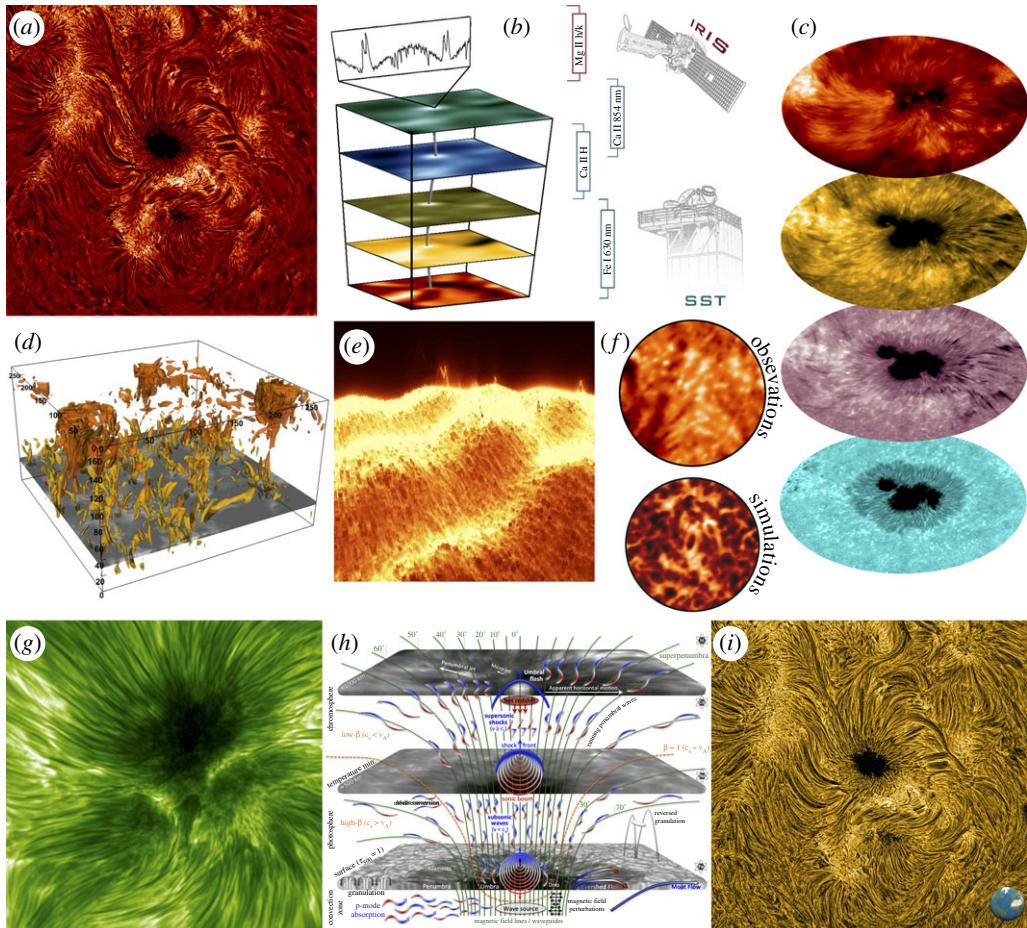


Figure 3. All nine of the potential cover art images that were submitted as part of the public engagement activities described in §2a. Captions for all panels of figure 3 are displayed in §2a, alongside the corresponding credits for each submission. During the online voting process, over 800 independent votes were registered spanning 18 countries.

(b) Multi-layer observations of a small-scale magnetic element through the lower solar atmosphere with the Swedish 1m Solar Telescope (SST) and Interface Region Imaging Spectrograph (IRIS) explorer. For better visibility, the three-dimensional cube has been stretched in height. Swaying motion of the flux tube (due to propagation of MHD transverse waves) and heating signatures (diagnosed as enhanced emission cores in the IRIS Mg II k spectra) are evident.
Image Credit: Shahin Jafarzadeh and RoCS.

(c) A stack of sunspot images captured in the Ca II spectral line at 854.2 nm by the IBIS spectral imaging instrument at the Dunn Solar Telescope in New Mexico, USA. The blue, purple, yellow and red coloured images sample different parts of the calcium spectral line and reveal the structuring of the sunspot atmosphere from the photosphere (blue) through to the upper chromosphere (red). The dark sunspot umbra towards the centre of the field-of-view reveals much cooler material as a result of the strong magnetic fields inhibiting the convective mixing of the surrounding plasma.
Image credit: David B. Jess.

(d) Three-dimensional rendering of the vorticity channels in simulations of solar magnetoconvection. Vorticity channels associated with the presence of magnetic flux tubes are

highlighted in orange. The grey scale image at the bottom indicates the temperature below the solar surface.

Image credit: Elena Khomenko.

(e) An artistic rendering of wave motion in the lower solar atmosphere, where a powerful shader lab in the Unity⁴ game engine was used to synthesize the solar surface. With DirectX libraries and GPUs it was possible to create the desired wave-like effects to resemble motion in the Sun's atmosphere.

Image credit: Robert Sych and Adam Bielecki.⁵

(f) The image illustrates the solar chromosphere at around 1.2 mm wavelength from observations with the Atacama Large Millimeter/submillimeter Array (ALMA; top panel) and from realistic three-dimensional radiation magnetohydrodynamic simulations with the Bifrost code (bottom panel). Various types of waves and oscillations have been observed in these observations and simulations at different spatial scales.

Image Credit: SolarALMA, RoCS and the University of Oslo.

(g) Sunspots are large patches of magnetic field that appear prominently on the Sun's surface (photosphere). The image shows the chromosphere of a sunspot, revealing how the magnetic field also shapes the upper layers of the Sun's atmosphere, providing the hair-like structures called fibrils. The image is from the Ca II line (854.2 nm) observed with the Swedish Solar Telescope.

Image Credit: Richard J. Morton and Vasco M. J. Henriques.

(h) Wave dynamics in a sunspot observed with the ground-based Dunn Solar Telescope in New Mexico. The simultaneous scanning of multiple spectral lines in the visible to near-infrared range has allowed a fine sampling of the photosphere and chromosphere above the sunspot. Sunspot waves are detected throughout all atmospheric layers, from the lower photosphere to the upper transition region and corona.

Image Credit: Johannes Löhner-Böttcher.⁶

(i) Same image as panel (a), only now spatially sharpened through use of Multiscale Gaussian Normalization [23], with a life-size representation of the Earth depicted in the lower-right to provide a sense of scale.

Image credit: David B. Jess.

In order to promote engagement with the general public, the 9 submitted images were uploaded to a voting platform accessible by all academic staff, researchers, scientists, and members of the public. Links to the voting webpage were circulated via social media (Facebook, Instagram, Twitter, etc.) posts in order to reach maximum visibility around the globe. The voting process was open across a period of two weeks, and the image with the highest overall rating was selected for the cover art of the Special Issue of the *Philosophical Transactions of the Royal Society A*.

Following the two weeks of the public vote on potential cover art images, over 800 independent votes were logged. While the specific location of the voters remained anonymous, we were able to log the countries of origin for each vote. In total, 18 countries submitted votes, incorporating (in alphabetical order) Australia, Brazil, China, Germany, India, Iran, Ireland, Italy, Norway, Poland, Portugal, Russia, Singapore, Spain, Sweden, United Arab Emirates, UK and the USA. The most and least active countries during the voting process were the UK (541 votes) and Poland (4 votes), respectively. To better visualize the registered votes, a 'heat map' was created to show the widespread engagement that was possible with such online activities (figure 4), including participation from members of the general public. It can be seen from figure 4 that countries not directly affiliated with the Theo Murphy meeting (e.g. those displayed in figure 2) were still able to participate in the voting process, highlighting the power of modern social media platforms.

⁴<https://unity.com/>.

⁵<http://bit.ly/sunshaderunity>.

⁶See the PhD thesis of Johannes Löhner-Böttcher for further information: <https://freidok.uni-freiburg.de/data/10748>.

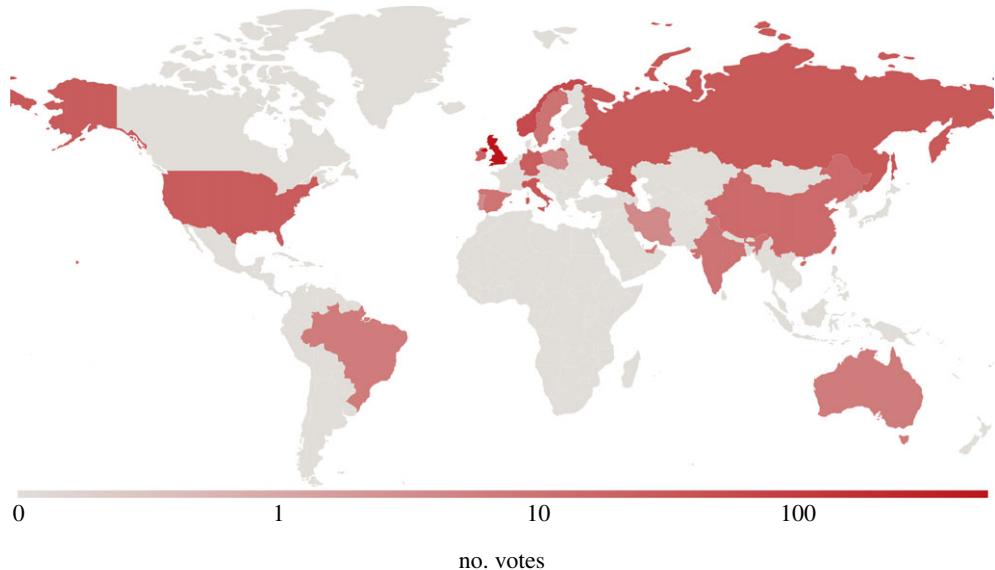


Figure 4. World map depicting the number of votes registered per country as part of the cover art selection process, with the white-to-red colour bar placed on a log-scale to better reveal countries with small voting statistics. Image data compiled by Shahin Jafarzadeh, displayed courtesy of <https://www.amcharts.com>, and based on the public voting platform produced by the WalSA team.

(b) Simulations of the solar atmosphere

Starting with high-resolution simulations of the base of the photosphere, Fleck *et al.* [24] examine and compare wave propagation characteristics across a number of internationally recognized magnetohydrodynamic (MHD) codes. The authors find troubling conclusions, in that not all MHD simulations display consistent wave signatures, highlighting the need for future collaborative efforts to ensure wave phenomena at the base of the visible photosphere are accurately and consistently replicated in these prevalent simulations. Introducing more concentrated magnetic fields to the simulation domain in the form of a magnetic flux sheet, Keys *et al.* [25] investigate the accuracy of Stokes inversions for prominent photospheric line profiles, including the 6301 Å and 6302 Å line pair, and establish whether accurate atmospheric parameters can be returned for typical spatial resolutions synonymous with modern (and upcoming) ground-based observatories. The authors find that the inversions they employ return temperatures, line-of-sight magnetic fields and line-of-sight velocities comparable to the original input numerical atmosphere, even with spectral asymmetries introduced from the generation and propagation of waves in the atmosphere. These are exciting results, since it means the improved spatial, temporal and spectral resolutions expected from the next generation of ground-based and space-borne telescopes will be able to accurately uncover and characterize wave phenomena on the smallest spatial scales achieved to date.

As waves continue to propagate into the upper solar photosphere and chromosphere, the associated plasma motions encounter the increasing influences of ambipolar and Hall effects. Khomenko *et al.* [26] examine how the ambipolar and Hall terms affect the vorticities seen in three-dimensional simulations of magneto-convection. The authors find that ambipolar diffusion results in a reduction of vorticity in the upper chromosphere, with vortical perturbations being dissipated and converted into thermal energy. Conversely, the authors find that the Hall effect acts to strongly enhance the vorticity. When the Hall effect is included, the authors find that the magnetic field is more vertical in nature and forms more flux-tube like structures that are long-lived, with the enhanced Hall effect possibly stabilizing the tubes against convective motions.

These vertical flux tubes act as funnels channelling vortical motions to upper layers, which are dissipated leading to temperature increases in the chromosphere that can endure for a significant amount of time.

Once waves, in particular slow magnetoacoustic modes, begin to traverse the solar chromosphere, they often steepen into local shock fronts, manifesting as intensely heated concentrations of plasma that outline the motion path of the wave. Through examination of cutting-edge radiative MHD Bifrost simulations, Eklund *et al.* [27] investigate the evolution of brightness temperatures coupled to a strong developing shock wave. The authors demonstrate that millimetre brightness temperatures (i.e. consistent with radio observations from the Atacama Large Millimeter/sub-millimeter Array (ALMA); [28,29]) efficiently track upwardly propagating shock waves in the middle chromosphere, which provides an important diagnostic tool to better understand small-scale dynamics across these turbulent regions of the Sun's atmosphere.

(c) Gravity waves

In relatively weak magnetic regions of the lower solar atmosphere, gravity waves with frequencies shorter than $\lesssim 2$ mHz (periods $\gtrsim 500$ s) have been identified in both observations and simulations [30–33]. Such waves have been found to have larger energy flux, by approximately one order of magnitude, compared to co-spatial acoustic waves [34], and thus can potentially contribute towards heating of the chromosphere and beyond. Detection of the gravity waves in the solar atmosphere has, however, been a challenging task. Using a three-dimensional cross-correlation technique involving time series of vertical velocities measured at different atmospheric heights, Calchetti *et al.* [35] propose a new approach to directly identify and characterize gravity waves in the lower solar atmosphere. The authors further validate their method using an observational dataset as well as a simple numerical model.

Internal gravity waves are mainly driven by convective updrafts reaching the stratified atmosphere above, with low frequency ultraviolet brightness fluctuations believed to be the result of these waves dissipating in higher regions [36]. The role of magnetic fields in the propagation of internal gravity waves is less clear. Likewise, the link between brightness fluctuations in internetwork regions and internal gravity waves is not fully resolved. Using three-dimensional simulations of the near-surface obtained with the CO⁵BOLD code [37], Vigeesh *et al.* [38] find that in low layers the magnetic field does not play a significant role in the propagation properties of internal gravity waves. However, the authors find that in higher layers (approx. above 0.4 Mm) the average magnetic field orientation dictates the propagation properties, with internal gravity waves reflected downwards in predominantly vertical field models while propagating freely upwards in horizontal and non-magnetic models. The authors also suggest that wave-breaking in internetwork models may result in the ultraviolet brightness fluctuations reported in the literature.

(d) Pioneering ALMA radio observations

Transitioning into radio observations of the solar atmosphere, Jafarzadeh *et al.* [39] and Guevara Gómez *et al.* [40] study pioneering ALMA observations to search for wave signatures in brightness temperature values that are coupled to the chromospheric plasma. Examining the brightest (and therefore hottest) locations of a plage/enhanced-network region observed by ALMA, Guevara Gómez *et al.* [40] uncover significant oscillations in brightness temperature, size and horizontal velocity, which are believed to be combined signatures of fast sausage-mode and Alfvénic waves in these small structures. Turning attention towards ALMA observations demonstrating varying degrees of magnetic complexity, Jafarzadeh *et al.* [39] highlight the potential challenges when interpreting radio observations. Notably, the authors find that the wave power spectra vary from dataset to dataset, which is further examined in terms of the underlying magnetic topology. Importantly, Jafarzadeh *et al.* [39] propose that more theoretical and modelling work is required to understand why only a very small fraction of the ALMA data examined show

peak power near 5.5 mHz, which is in contradiction to other chromospheric diagnostics where very pronounced oscillations are regularly found in this band.

(e) Observations of large-scale solar magnetism

As the concentrations of solar magnetism continue to grow, larger-scale structures begin to form in the Sun's atmosphere, including the formation of solar pores. These highly magnetic elements are studied by Gilchrist-Millar *et al.* [41], who captured photospheric spectropolarimetric profiles of the infrared Si I 10 827 Å absorption line for a collection of pores located with the same field-of-view of the Dunn Solar Telescope. The authors employ polarimetric inversion routines and high time resolution data products to examine the height dependency of wave energy flux in the lower solar atmosphere. Importantly, Gilchrist-Millar *et al.* [41] discover that while pore structures act as efficient wave conduits to guide energy flux into the outer regions of the Sun's atmosphere, the photospheric layers rapidly damp the embedded wave energy by several orders of magnitude. These results, including the short damping lengths uncovered, pose important questions for next-generation facilities that should be able to probe such features with unprecedented polarimetric precision.

Fully formed sunspots are a visually striking manifestation of concentrated magnetic fields in the Sun's atmosphere. Through novel filtering techniques, Sych *et al.* [42] examine how wave activity in the most intensely magnetic umbral locations allows the embedded fine structure of the sunspot to be probed with high levels of precision. The authors find that the motion path of visible wave trains occurs along preferential directions depending upon the magnetic field inclination angles present within the umbra. Sych *et al.* [42] propose that small-scale umbral structuring may be responsible for the creation of ubiquitous umbral flashes, and highlight the important need for next-generation larger-aperture solar telescopes to unequivocally answer this question. In keeping with umbral wave observations, Albidah *et al.* [43] examine a sequence of high-cadence H α images that captured a near circularly symmetric sunspot using the HARDCam instrument on the Dunn Solar Telescope. Applying cutting-edge Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD) techniques, the authors are able to identify low-order MHD wave modes as coherent oscillations across the entire sunspot umbra. Through examination of spatial and temporal orthogonality, Albidah *et al.* [43] provide evidence to support the co-existence of sausage *and* kink modes within the same magnetic structure, which demonstrates the suitability of their techniques to more widespread solar observations of sunspot waves.

One of the largest and most magnetically intense sunspots of the previous solar cycle passed through the Earth's line-of-sight during May 2016, and was captured by the Interferometric Bi-dimensional Spectrometer (IBIS; [44]) Fabry-Pérot instrument at the Dunn Solar Telescope. Using chromospheric Ca II 8542 Å spectropolarimetric imaging scans, Stangalini *et al.* [45] investigate the relationship between intensity and circular polarization fluctuations observed within the large-scale sunspot. The authors find clear correlations between the intensities and magnetic signals, suggesting the detection of Alfvénic perturbations. This has important implications for investigations of chromospheric mode conversion physics [13,19], in addition to shining light on the role of magnetic waves in the generation of the First Ionization Potential (FIP) effect that is ubiquitously observed in the solar corona, in the solar wind and solar-like stellar coronae [46], and was therefore proposed as a potential mechanism to trace back the solar wind to its atmospheric source.

The dynamics displayed in high-resolution spectral sunspot observations often creates challenging problems for researchers attempting to understand the mechanisms responsible for generating asymmetric, centrally reversed and/or heavily skewed line profiles. The interplay between source functions and opacity effects often requires the fitment of two (or more) profiles to any given spectral line in order to best constrain the underlying dynamics. This is a time consuming endeavour to perform manually, prompting MacBride *et al.* [47] to apply machine learning techniques to this challenging problem to accurately, efficiently and repeatedly extract the key components of the observed line profiles. The authors employed a training dataset based

on IBIS Ca II 8542 Å sunspot observations, and when applied to high-cadence spectral scans it was able to accurately fit over 600 000 spectral profiles in approximately 2 h, with the potential to further parallelize via multiple CPU cores and/or the implementation of GPUs. MacBride *et al.* [47] highlight the potential of their techniques to be applied to upcoming observations from the National Science Foundation's Daniel K. Inouye Solar Telescope (DKIST; [9]) in real time, thus providing important wave diagnostics live at the observing site to help pinpoint regions of interest for specific wave studies.

As observations move away from the umbral core of a sunspot, the magnetic field lines begin to more heavily incline with respect to the solar normal. Using high-resolution Ca II 8542 Å observations from the Swedish 1m Solar Telescope, Morton *et al.* [48] examine chromospheric super-penumbral fibrils that span out radially from the underlying sunspot. Through extensive statistical analyses, the authors find that these narrow structures show ubiquitous wave-like motions that can be interpreted as MHD kink waves, which are broadly consistent with previous observations of chromospheric transverse waves in quiet Sun fibrils. Morton *et al.* [48] speculate that these motions may be able to improve our understanding of how MHD wave energy is transferred through the atmosphere of a sunspot. Zooming out to incorporate the full extent of a sunspot active region, the larger-scale interactions of the embedded magnetic fields provide a number of distinct locations from which unique wave relationships can be examined. One such example involves the formation of oscillatory phenomena in the vicinity of a polarity inversion line. Norton *et al.* [49] harness the large field of view of the Helioseismic Magnetic Imager (HMI; [50]) onboard SDO to examine the amplitudes and phase relations of oscillations existing in quiet Sun, plage, umbral, and polarity inversion line (PIL) locations of an active region. The authors' derived values are consistent with slow standing or fast standing surface sausage mode waves, leading Norton *et al.* [49] to propose that line width variations (alongside their phase relations with intensity and magnetic oscillations) may offer a novel new way to further differentiate wave mode mechanics in the solar atmosphere. Importantly, Norton *et al.* [49] reveal evidence for the mode conversion of Doppler oscillations into magnetic waves, highlighting the important interplay of MHD waves across all layers of the Sun's atmosphere.

3. Conclusion and future directions

Solar physics research is ideally positioned to make rapid discoveries over the coming decades, with the imminent full-scale operation of the 4 m DKIST facility, in addition to ongoing work linked to the development of the 2 m Indian National Large Solar Telescope (NLST; [51]) and the 4 m European Solar Telescope (EST; [52]). In addition to these ground-based observatories, next-generation balloon-based and space-borne facilities, including the continually updated SUNRISE observatory [53,54], Solar Orbiter [55] and the JAXA M-class Solar-C [56] future mission, will help probe the photospheric and chromospheric interactions with other regions of the solar atmosphere on unprecedented scales. In particular, novel instrumentation, including fibre-fed imaging spectrographs (e.g. the Diffraction-Limited Near-Infrared Spectropolarimeter, DL-NIRSP; [57]), will provide the community with the much anticipated spectral, polarimetric, spatial, and temporal resolutions necessary to accurately constrain the rapidly evolving, yet often small amplitude fluctuations associated with wave phenomena in the Sun's atmosphere.

In addition to the observational improvements coming online over the next decade, researchers will also be able to capitalize on next-generation high performance computing (HPC) infrastructures that are currently being built and updated. Within the UK, the Distributed Research using Advanced Computing⁷ (DiRAC) and ARCHER⁸ HPC systems provide over 6 petaflops of compute capability, while international HPC services such as La Red Española de Supercomputación⁹ (RES, Spanish Supercomputing Network), the Norwegian academic

⁷<https://dirac.ac.uk/>.

⁸<http://www.archer.ac.uk/>.

⁹<https://www.res.es/en>.

e-infrastructure¹⁰ and the NASA Pleiades¹¹ supercomputer can boost the compute capabilities up into the tens of petaflops. Such evolving HPC facilities are crucial for the accurate replication of physics, particularly down to the spatial and temporal scales imminently visible by the newest observing facilities.

The publications presented in the current Special Issue demonstrate the computational and observational challenges that await the widespread community. However, it is clear that the next generation of committed solar physicists, alongside the friendly, inclusive, collaborative environment and knowledge base brought by senior researchers and academics, can readily foster solutions to any potential problems raised in the field of oscillations and waves in the lower solar atmosphere. We therefore look forward in anticipation to the new era of understanding that will be brought to fruition by the newest researchers, observatories, and computing facilities over the decades to come.

Data accessibility. This article has no additional data.

Authors' contributions. D.B.J., P.H.K., M.S. and S.J. acted as Guest Editors for the '*High-resolution wave dynamics in the lower solar atmosphere*' Special Issue of the *Philosophical Transactions of the Royal Society A*. All authors drafted, read and approved this introduction.

Competing interests. We declare we have no competing interests.

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